Beam-beam simulations in FY08
Second quarter results

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Contents

1 FNAL report

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Executive Summary. Diffusion coefficients were calculated and compared with measurements for three different RHIC collision runs. They were applied to the diffusion equation solver to estimate the evolution of beam intensity and emittance. These were compared with experimental data. In addition, particle tracking was done for the wire compensation experiment. Resistive wake field module and the symplectic synchro-beam module were added to BBSIM.

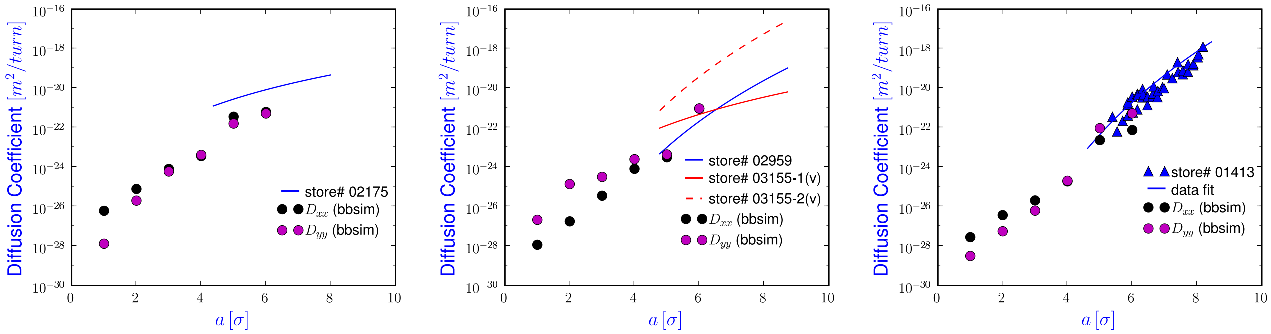
1.1 Diffusion Equation Solver

In this part of the report we concentrate on the numerical simulations of three RHIC runs [1]: deuteron-gold, gold-gold, and proton-proton operations. Even though they consist of different species of particles and operation conditions, their beam property can be described by a macroscopic parameter such as diffusion coefficient in action-angle space. The diffusion coefficient contains the effects of nonlinearities present at the accelerators, for example, beam-beam interactions, IR multipoles, sextupoles, etc. In BBSIM code, we have implemented the diffusion coefficient module which calculates the coefficients over two-dimensional action space. Table 1 gives a list of RHIC runs and their simulation conditions which are used to calculate the diffusion coefficients. In the simulations two head-on collisions at IPs 6 & 8 are considered, but no long-range interactions.

	species	energy (Gev/n)	beam intensity	emittance $(\pi\mu m)$	tunes
run-08	proton	100	1.35×10^{11}	20	$(0.685, 0.695)$
	proton	100	1.35×10^{11}	20	$(0.695, 0.685)$
run-08	deuteron	100	1.2×10^{11}	17	$(0.235, 0.225)$
	gold	100	1.0×10^{9}	17	$(0.225, 0.235)$
run-07	gold	100	1.0×10^{9}	18	$(0.220, 0.231)$
	gold	100	1.0×10^{9}	18	$(0.232, 0.228)$

Table 1: a list of RHIC runs and simulation conditions.

Since diffusion coefficients are calculated at two-dimensinal action space, they are averaged at the same action to compare the simulation with the measurement of coefficients and plotted with the measurements as shown in Fig. 1. Due to the limitation of measurement, the diffusion coefficients are not measured at small action. On the contrary, BBSIM has a difficulty in



(a) (b) (c)

Figure 1: Plots of diffusion coefficients of (a) proton-proton, (b) deuteron-gold, and (c) gold-gold stores of RHIC. The coefficients are calculated at Blue ring. In the plots, store#'s are measured and fitted by R. P. Fliller [2].

calculating the coefficient at large action, because the particles are lost very quickly as particle's initial action is large. Figure 2 shows the horizontal and vertical emittance growth and beam intensity evolution for deuteron-gold store. The intensity is estimated by the zeroth moment of density, i.e., $\langle \rho(t) \rangle = \int \rho d\vec{J}$, and the emittance is by the first moment of density, i.e., $\varepsilon_x \equiv \langle \rho(t) J_x \rangle = \int \rho J_x d\vec{J}$.

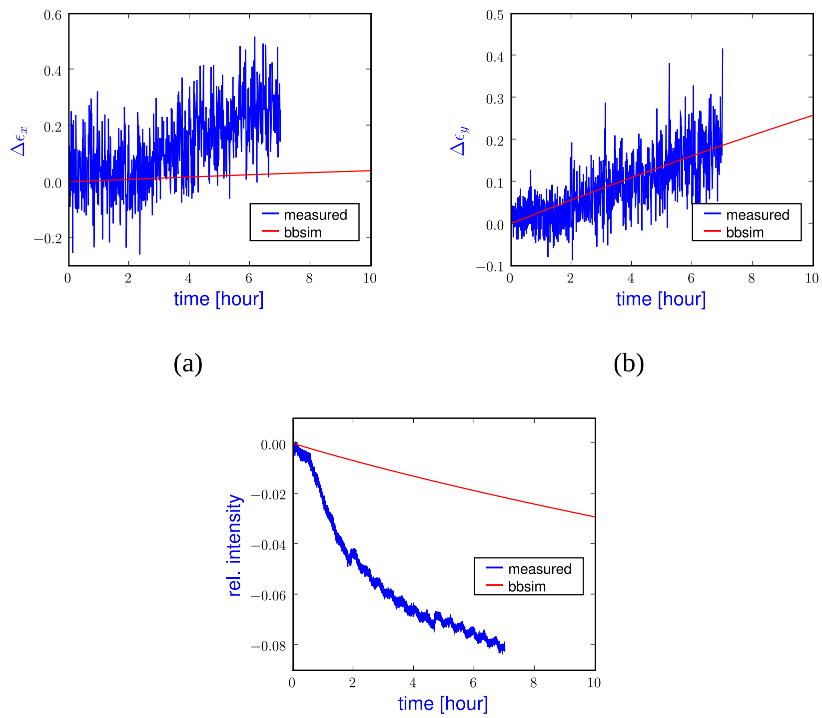
1.2 Wire Compensator Simulation of RHIC with BBSIM

We do numerical simulations for wire compensator experiment which was performed at the end of deuteron-gold run in January, 2008. The simulation parameters are the same as those of run-08. The wire parameters are as follows: wire current is 50A, wire length 2.5m, and wire separation distance 26-38mm. Figure 3 shows the tune shift, dynamic aperture, and beam loss rate according to the wire separation distance.

1.3 Code Improvements

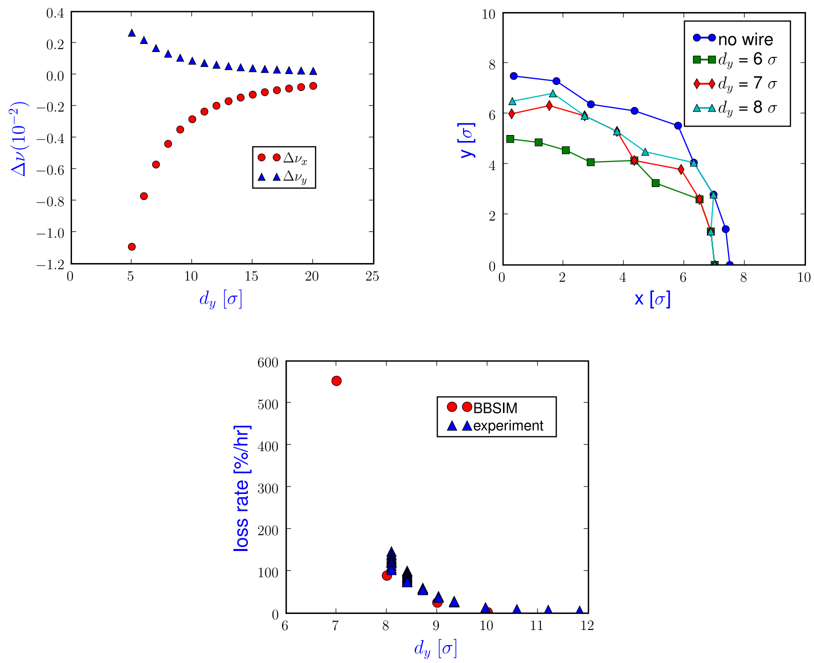
- *Resistive wall wake field*: Wake fields in accelerator can be categorized into geometric and resistive wall wake fields. The geometric wake field due to the change of cross section of accelerator components is not implemented in BBSIM yet. However, the resistive wall wake field in long-range regime is implemented and tested. The transverse wake kick received by a test particle at position z is given by [3]

$$\Delta \vec{r}_{\perp}{}' = -\frac{N r_0}{\gamma}\hat{r}\Delta r \cos\theta \int_z^{\infty} dz' \rho\left(z'\right) W_1\left(z-z'\right), \qquad (1)$$



(a) (b) (c)

Figure 2: Plot of emittance growth of deuterons in the deuteron-gold store 9572 of RHIC which is calculated by the diffusion solver. (a) horizontal emittance, (b) vertical emittance, and (c) relative intensity.



(a) loss rate

Figure 3: Plot of (a) tune shift at zero amplitude versus the beam-wire separation, (b) dynamic aperture, and (c) beam loss rate versus bwam-wire separation distance. Experiment data are taken by W. Fischer and N. Abreu at BNL.

where Δr is the transverse offset, $r_0 \equiv qq_*/4\pi\varepsilon_0 m_0 c^2$ the classical radius of the particle, and W_1 the wake function. Only dipole term is included because higher order wake field terms $\left(W_{m\geq 2}\right)$ are negligible in most cases. The longitudinal wake kick is applied as follows:

$$\Delta\delta = -\frac{Nr_0}{\gamma}\int_z^\infty dz'\,\rho\left(z'\right)W_0'\left(z-z'\right). \tag{2}$$

- *Finite bunch length effect of beam-beam interaction*: To consider the bunch length effect, the synchro-beam framework [4] is applied in BBSIM. The synchro-beam map includes beam-beam interactions due to the longitudinal component of the electric field as well as the transverse components.

1.4 Plans for 3rd and 4th quarters

- 3rd Quarter
  - Simulations of wire compensation with beam-beam interaction module are performed for both RHIC and LHC.
  - Coherent beam-beam module is added to BBSIM.
- 4th Quarter
  - Coherent beam-beam module is extensively tested for RHIC or LHC.

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2 SLAC report

Author: A. Kabel

2.1 Transition to LHC lattice descriptions

The MAD-X lattice files made available by CERN make use of more element types and syntax elements of MAD-X than the lattices I had to process for RHIC. Having `plibb` process these files required more effort than initially assumed. The libraries had to be extended to treat

- Rectangular bends; these are modeled as sector bends with two thin (chromatic) wedge maps
- Variants of MAD's markers, instruments, kickers with finite lenghts
- Generalized finite-length multipoles with mixed skew and upright components
- '`aperture`' parameters
- The `bv` parameter that expresses the bend orientation for a magnet with a dipole component common to two rings in dependence of the element type and beam direction

.

`plibb` is now able to digest the full LHC lattice as generated by the script files provided by CERN. Twiss quantities have been checked against MAD-X and show agreement within the expected accuracy range ($\approx 10^{-7}$. There is still a deviation in the chromaticity of $\approx 10^{-2}$ when it is corrected down to 1 unit. This has to be checked more carefully.

The very limited parameter file format of `plibb` has been replaced with two embedded scripting languages (Lua and Python). This has drastically simplified life, as it makes it very easy to recalculate simulation parameters, write simple loops, periodically output data from within the parallel simulation code without having to recompile C++ code. Also, it makes all tracking routines in `plibb` available for interactive use, e.g., to check lattices, calculate transfer matrices or Twiss functions.

2.2 BTF comparisons

I have collaborated with J. Qiang of LBL to bring into agreement our respective codes and the RHIC BTF measurements in the presence of the correction wire. There is a series of problems with the measurements and their simulations which we could not resolve.

The simplest wire model (cut-off infinite wire) and 1st order perturbation theory gives tune shifts in good agreement with the measurements done in 5/07. Both codes reproduce these by tracking, and, for `plibb`, map analysis; any discrepancies could be traced back to the use of different lattice files and are resolved.

Getting the BTF profile to agree among codes and with measurements is harder. `plibb` showed good agreement in relative position and size of the synchrotron sidelobes; as it uses a 6x6 formalism throughout, they are determined completely by beam and RF station parameters. Ji's code uses a lumped $4 \times 4/6 \times 6/4 \times 4$ chromatic mapping at a single location in the ring with the synchrotron tune as a free parameter, which may explain the different results for the longitudinal contribution of the profile. Also, I noted that the number of FFT sample points will have an impact on the shape of the profile, we should agree on a value, ideally the one used by the measurement.

Finally, the positions of the central tune in simulation and experiment do not show the expected agreement. This seems strange as the same experiment provided tune data consistent with perturbation theory. The higher-current profiles show a distinct coupling of the respective other transverse plane; at least for the RHIC Yellow beam, N. Abreu has reported on tune measurements compromised by transverse coupling. I could not reproduce the transverse coupling effect by offsetting the current wire by any reasonable amount.

If we are to use the BTF for any further benchmarking, we need to check (1) the sample depth of the BTF measurement, (2) whether or not the tune measurement happened under different parameter sets than the BTF measurement, (3) if there are any insights in the nature of the coupling.

2.3 Code Additions

2.3.1 IBS

The IBS algorithm described in the last report has been integrated as a module into `plibb`. There are still some minor problems to fix; the numeric accuracy of the local kernel integration is unsatisfactory, as is its speed behavior. Also, there is a discrepancy between rest frame and accelerator frame calculations (which should agree) that needs to be resolved.

2.3.2 Electron Lens

The electron lens may be an interesting candidate for a compensation mechanism at LHC and RHIC. A straightforward model is that of a laminar current with flat distribution in r, which leads to

$$\delta \vec{x}_{\perp}' = k\mu \frac{\vec{r_{\perp}}}{r_{\perp}^2}, r_{\perp} > R$$

$$\delta \vec{x}_{\perp}' = k\frac{\vec{r_{\perp}}}{R^2}, r_{\perp} \leq R$$

with effective strength

$$k = \frac{e_p \mu_0 I}{2\pi\gamma_p}\left(1 \pm \frac{1}{\beta_e}\right)$$

This simple model has been implemented in `plibb`, I am currently checking against analytical tune spreads and shifts for different cases. (inside/outside/overlapping). The next steps would be tracking runs with LHC and RHIC lattices to see if the Lifetime can be positively affected.

2.4 Plans for 3rd and 4th quarters

Code improvements:
The IBS component needs to be benchmarked, the problem of discrepance between lab frame and rest frame has to be understood. It also has become clear that the chromatic lumping method fails in some instances (namely when bracketing a single dipole), in this case, a deficient eigenvector system occurs. This needs to be addressed, but requires a rewrite of the algorithm in more general form.
Additional physics:
There is no crossing angle present in the weak-strong module, this has to be added to run LHC simulations. I have added a long-range frequency domain wakefield module, this should be complemented with a short-range time-domain one. The ultimate goal would be to be able to simulate a crab cavity.

The PIC module for strong-strong will be changed to incorporate some of the fast interpolators used in out PIC3P gun code; this will allow to use higher-order basis functions and reduce noise without impacting runtime.

3 LBL report

Author: J. Qiang

3.1 Introduction

During this period of report time, we have carried out studies of modeling BTF signal at RHIC with compensation wire and preliminary studies of beam-beam interactions at LHC with local crab cavity correction. The simulated tune shifts from the BTF signal agree well with the analytical model [1] but shows discrepancy with the measurement. For the studies of beam-beam interaction at LHC with local crab cavity correction, we observed significantly luminosity improvement by using local crab cavity deflection 90 degree from the cross angle collision point. However, this gain of luminosty can be lost due to random phase errors inside the RF cavities.

3.2 Simulation of BTF Signal at RHIC

During the 1st quarter report period, we implemented a beam transfer function (BTF) diagnostic model into the BeamBeam3D code. This model was tested using the measurement information at http://www.agsrhichome.bnl.gov/AP/BeamBeam/BTF/. Figure 4 shows the horizontal BTF signal of the blue beam measured at RHIC with zero current of compensation wire and 50 A compensation wire and 30 mm separation. It is seen from this measurement, the major tune shift due to the conducting wire is about 0.001. Besides the sychrotron sideband, there is another peak near 0.226 that might be due to the coupling from the vertical plane.

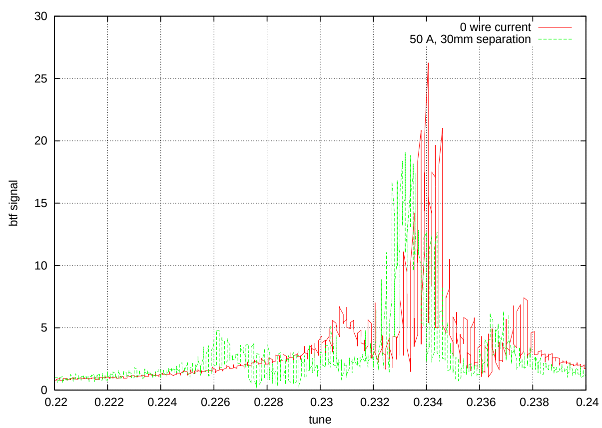

Figure 4: Measured horizontal BTF signal of blue beam with/without compensation wire current at RHIC.

Using the BeamBeam3D code, we simulated the BTF signal for those measurements. The simulated BTF signals are given in Figure 5 and Figure 6. With zero current the wire compensation, the simulation reasonably reproduced the measured signal for the blue beam. However, with 50 A current and 30 mm separation, the simulation showed much larger tune shift than the measurement as shown in Figure 6. We have repeatedly checked the wire compensation model used in our simulation and could not identify some implementation errors. As a test of the wire compensation model in the BeamBeam3D, we also cacluated the tune shift measured from our BTF signal as a function of vertical separation and compared with analytical calculation given by B. Erdelyi and T. Sen [1]. These results are given in Figure 7. The simulated tune shifts from the BeamBeam3D BFT signal agree with the analytical model very well. However, it is seen from Figure 4 and Figure 6 that the measured tune shift is only about 0.001, while the simulated tune shift is about 0.003. This discrepancy could be due to 1) the MADx lattice parameters used in the simulation is not the same as the measured case; 2) some nonlinear or coupling effects that are not included in the simulations changed the tune shift in the measurement; 3) some mislabeling of the reported measurement data. We have carried out some detailed discussions with A. Kabel at SLAC. So far, we have not reached any definite conclusion. Further studies may be needed to solve this discrepancy.

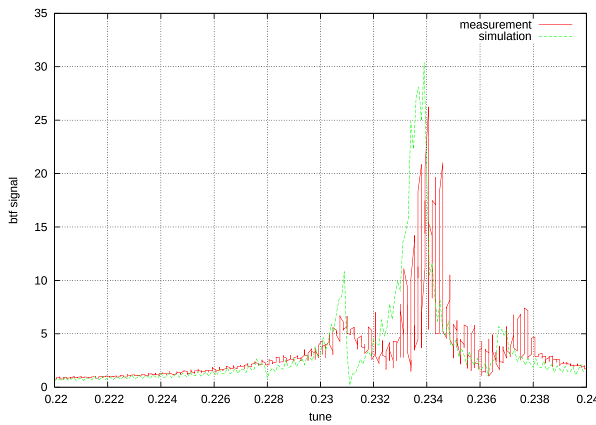

Figure 5: Measured and simulated horizontal BTF signal of blue beam without compensation wire current at RHIC.

3.3 Prelimnary Studies of Beam-Beam Collisions with Crab Cavity at LHC

In this quarter, we also implemented a nonlinear thin lens model of crab cavity into the BeamBeam3D code. Here, we have assumed 90 degree separation between the crab cavities and the interaction point. There are four crab cavities for each interaction point. To test the crab cavity model, we simulated the strong-strong beam-beam interactions at LHC with a single collision point, 0.15 mrad half crossing angle, and nominal parameters used in reference 2 [2]. Figure 8 shows the luminosity at LHC as a function of turns with 0.15 mrad cross collision and with 0.15

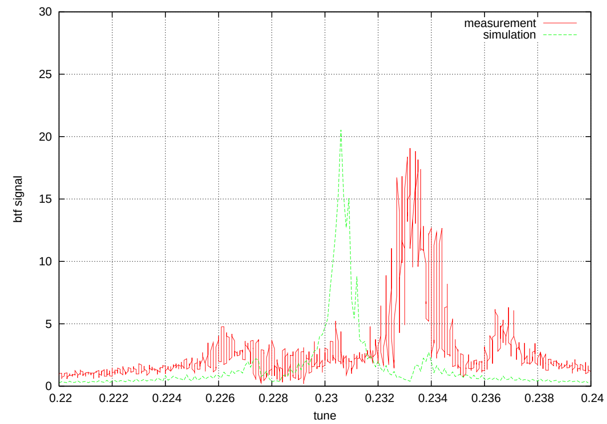

Figure 6: Measured and simulated horizontal BTF signal of blue beam with 50 A compensation wire current and 30 mm vertical separation at RHIC.

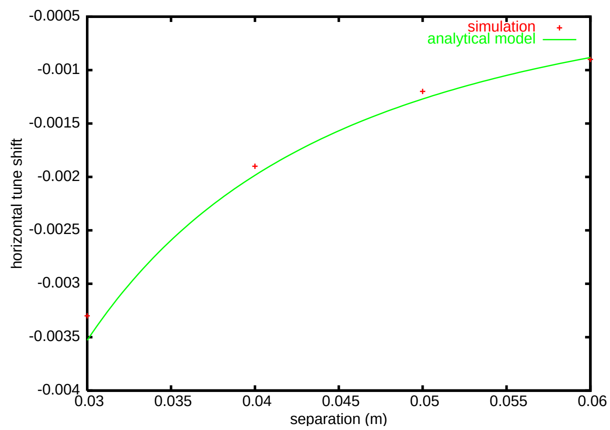

Figure 7: A comparison of simulated tune shift as a function of wire separation with analytical model.

mrad cross collision and local crab cavities. It can be seen that by using the local crab cavity deflection, the luminosity has been improve by about 18%. This recovers the geometric luminosity loss due to crossing angle collision. Figure 9 shows the evolution of the square of rms sizes with and without crab cavity. Due to the deflection of the beam along the design trajectory by the crab cavity, the projected rms size actually increases. The phase errors in the RF cavities can cause a transverse offset of the beam at the interaction point. These phase jitters are not white noise but with some frequency spectrum as measured from the KEK-B crab cavities. To model these errors, we have used a colored Ornstein-Uhlenbeck noise with exponential dependence of correlation. This fluctuation is sampled from a sequence of random numbers following the model in reference 2 and 3 [2, 3]. Figure 10 shows the luminosity evolution without transverse offset errors and with 0.85 um and 1.7 um offset errors and 100 turn correlation. With 1.7

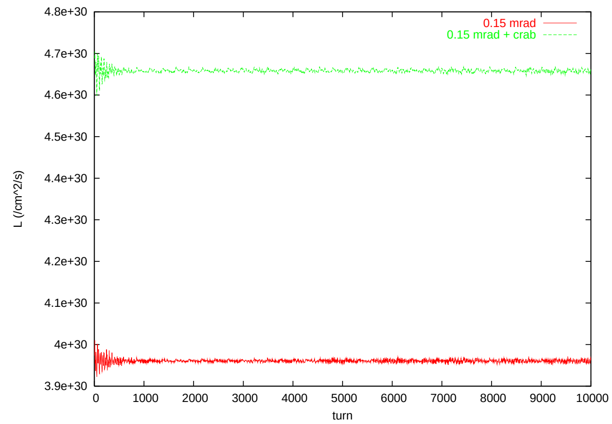

Figure 8: Luminosity evolution with 0.15 mrad half crossing angle and with/without crab cavity.

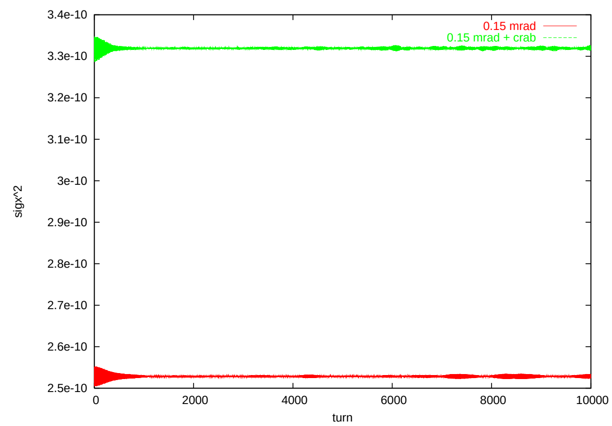

Figure 9: Square of rms size evolution with 0.15 mrad half crossing angle and with/without crab cavity.

um offset error amplitude that corresponds to 5 degree of phase error amplitude, the luminosity has decreased by 8% at the end of 10,000 turns. Figure 11 shows the evolution of the square of rms sizes without and with random phase errors. A few percentage growth at the end of 10,000 turns is observed for 0.85 um offset error amplitude.

3.4 Plans for 3rd and 4th quarters

In the next 2 quarters of FY08, we will study the effects of long-range beam-beam interaction on the LHC luminosity using a strong-strong model. Then we will study the benefits of wire compensation of the long range beam-beam interactions to the LHC luminosity.

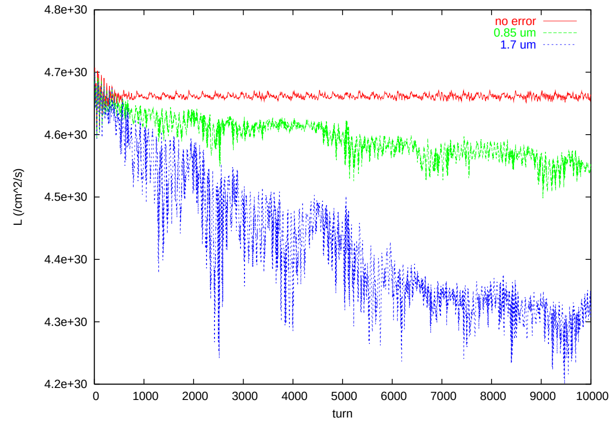

Figure 10: Luminosity evolution without/with 0.85 um and 1.7 um noise amplitude

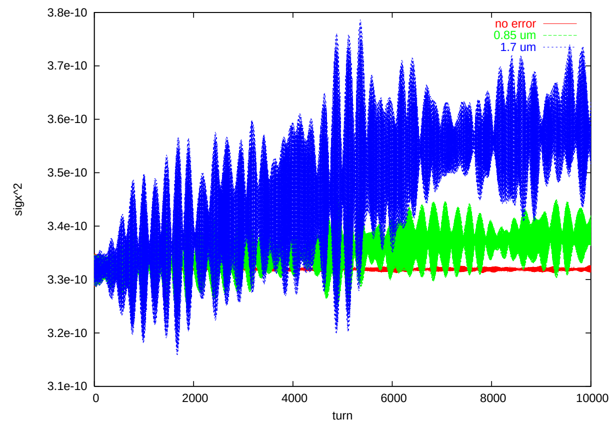

Figure 11: Square of rms size evolution with 0.15 mrad half crossing angle and with/without crab cavity.

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